

# EXHIBIT 4



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Chapter 10

## 10.4 GREEN MACHINING

The final shape and tolerances cannot always be achieved by pressing, casting, and plastic forming. In many cases, the final dimensions are achieved by surface grinding or other finishing operations following the densification step. This requires diamond tooling and can be very expensive. Final machining can often be avoided by machining the ceramic particulate compact prior to densification. This is referred to as *green machining*.

Unfired green material is relatively fragile, and great care is necessary in the design and fabrication of the tooling and fixturing so that the parts can be accurately and uniformly held during the various shaping operations. In addition, the machining parameters must be carefully controlled to avoid overstressing the fragile material and producing chips, cracks, breakage, or poor surface.

Holding of the compact for machining is typically accomplished either by simple mechanical gripping or by bonding or potting with a combination of beeswax and precision metal fixtures. The part must be held rigidly, but with no distortion or stress concentration.

Once a ceramic part has been secured rigidly in a fixture, machining can be conducted by a variety of methods—turning, milling, drilling, form wheel grinding, and profile grinding. Machining can be either dry or wet, depending on the binder present and whether or not the part has been bisque-fired.\* In either case, the compact is abrasive and results in tool wear. A wear land on the cutting edge as little as 0.1-mm (0.0039-in.) wide can cause a buildup of cutting pressure and result in damage to the ceramic.

It is possible to machine compacts with high-speed steel or cemented carbide cutting tools, but this is not recommended for all components or all green materials. In some cases, the tool dulls so rapidly that extreme care is necessary to avoid damage to the workpiece. Figure 10.71 summarizes a green machining study comparing several cutting-tool materials. A 5° positive rake and 10° clearance angle were used in the study. The compact diamond cost about 10 times as much as the tungsten carbide, but resulted in a significant cost saving in terms of increased life, less time changing inserts, and reduced risk of damage to the workpiece from a dull tool. The study was conducted with single-point turning on an engine lathe. Milling with a two-flute end mill at 61 surface meters/min (200 sfm) with compact diamond inserts showed the same life characteristics.

\*Fired at a high enough temperature to form bonds at particle-particle contact points, but not at a high enough temperature to produce densification.

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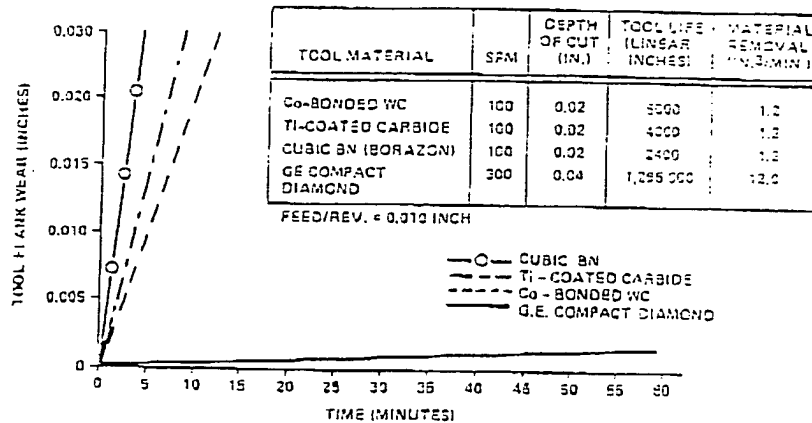


Figure 10.71 Tool wear for different tool insert materials for green machining of a presintered silicon compact in the fabrication of reaction-bonded  $\text{Si}_3\text{N}_4$ . (From Ref. 40).

Green machining can also be conducted with grinding wheels containing multiple abrasive particles bonded in a resin or metal matrix. Higher surface speed, broader contact, and decreased depth of cut are characteristic of this technique, resulting usually in a better surface and less chance of damage. Excellent tool life can be achieved, especially if a diamond abrasive is used. Furthermore, coarse abrasive can be used for roughing passes and fine abrasive for finishing. Formed wheels can also be used to produce a controlled and reproducible contour, as was discussed earlier in this chapter for green machining of spark plug insulators and oxygen-sensor electrolytes.

## REFERENCES

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2. O. J. Whittemore, Jr., Particle compaction, in *Ceramic Processing Before Firing* (G. Y. Onoda, Jr. and L. L. Hench, eds.), Wiley, New York, 1978, pp. 343-355.
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4. P. Duwez and L. Zwell, AIME Tech. Publ. 2515, *Metals Trans.*, 1, 137 (1949).